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Omnipotent Virtual Giant for Remote Human–Swarm Interaction

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***Abstract*— This paper proposes an intuitive human-swarm interaction framework inspired by our childhood memory in which we interacted with living ants by changing their positions and environments as if we were omnipotent relative to the ants. In virtual reality, analogously, we can be a super-powered virtual giant who can supervise a swarm of robots in a vast and remote environment by flying over or resizing the world, and coordinate them by picking and placing a robot or creating virtual walls. This work implements this idea by using *Virtual Reality* along with *Leap Motion*, which is then validated by proof-of-concept experiments using real and virtual mobile robots in mixed reality. We conduct a usability analysis to quantify the effectiveness of the overall system as well as the individual interfaces proposed in this work. The results reveal that the proposed method is intuitive and feasible for interaction with swarm robots, but may require appropriate training for the new end-user interface device.**

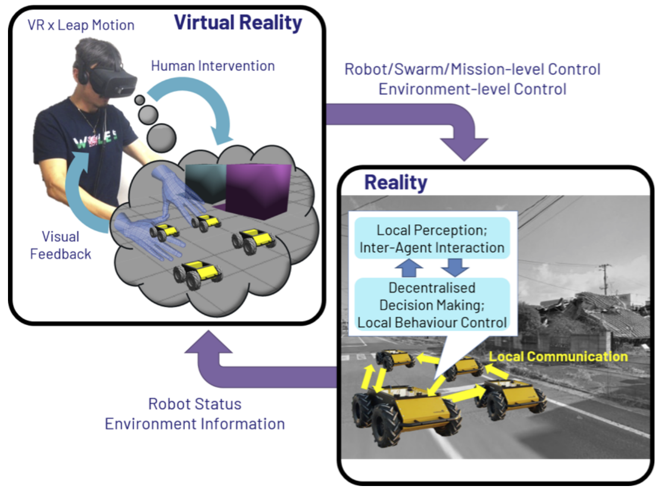

Fig. 1. The system architecture of the proposed Human-Swarm Interaction using *Omnipotent Virtual Giant*. A full demo video is available at https://youtu.be/2zXI6aRz3rw.

I. Introduction

Swarm robotics [1] is one of the promising robotic solutions for complex and dynamic tasks thanks to its inherent system-level robustness from the large cardinality. Swarm robotics research mostly involves a number of individually incapable robots (e.g., Mona [2]), which can be deployed for various of real-world applications, such as search and rescue [3], cooperative object transportation [4], target monitoring [5], etc.

Human-Swarm Interaction (HSI) is relatively a new research area that "aims at investigating techniques and methods suitable for interaction and cooperation between humans and robot swarms" [6]. One of the main difficulties of HSI compared with typical *Human-Robot Interaction* (HRI) is the fact that a large number of robots, due to swarm properties, should be involved efficiently, otherwise a human operator may be easily overwhelmed by enormous workload for control and situational awareness. In addition, it is highly expected that swarm robots are controlled by decentralised local decision-making algorithms [7]–[9], which generate a desired emergent group behaviour. Therefore, HSI should be *synergistic* with such self-organised behaviours by having interfaces of not only individual-level teleoperation but also subgroup-level and mission-level interactions. Furthermore, in practice, e.g. in an extreme environment, swarm robots would be deployed to a mission arena beyond the line-of-sight of a human operator. Therefore, considering these aspects, it is desirable to have a HSI framework by which a human operator can interact with remote robot swarms while keeping cognitive load as low as possible.

To this end, we propose an *Omnipotent Virtual Giant* for HSI, which is a super-powered user avatar interacting with robot swarms via virtual reality, as shown in Fig. 1. This was inspired by our childhood memory in which most of us have played with living ants by relocating their positions and putting obstacles on their paths as if we were omnipotent relative to them. Analogously, through the omnipotent virtual giant, a human operator can directly control individual robots by picking and placing them; can alter virtual environment (e.g. creating virtual walls) to indirectly guide the robots; and can fly around or resize itself to supervise the entire or a subgroup of the robots with different scopes. We implement this idea using *Leap Motion* with *Virtual Reality* (Sec. III), and validate the proposed HSI framework by using proof-of-concept real-robot experiments and by usability tests (Sec. IV).

II. Related Work

This section particularly reviews existing HSI methodologies and their suitability for remote operations. *Gesture-based* interactions have been popularly studied [6], [10]–[13]. A human's body, arm, or hand gestures are recognised by *Kinect* [11], electromyography sensors [12], [13], or onboard cameras [6], [10], and then translated to corresponding commands to robots. Such gesture-based languages probably require a human operator to memorise mappings

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from predefined gestures to intended commands, although some of the gestures may be intuitively used.

Augmented Reality (AR) has been utilised in [14], [15]. This method generally uses a tablet computer, which recognises robots and objects around a user through its rear-view camera. Using the touchscreen, the user can control the robots shown on the screen, for example, by swipe gestures. In [15], an AR-based method was tested for cooperative transport tasks of multiple robots. However, this type of interface is only available for robots in the surrounding environment.

Tangible interactions can be another methodology for certain types of swarm robots. The work in [16] presented tiny tabletop mobile robots, with which a human can interact *by actually touching* them. By relocating a few of the robots, the entire robots eventually end up with different collective behaviours. This tangible interface inherently does not allow any interfacing error when it comes to changing of a robot's position. Nevertheless, apart from position modifications, it seems not straightforward to include the other interfaces.

All the aforementioned interfaces require a human operator to be within proximity of robots. Instead, *virtual reality (VR)*-based interactions can be considered as an alternative for beyond-line-of-sight robotic operations. In a virtual space where a human operator interacts with swarm robots, the operator is able to violate the laws of physics, teleporting [17] or resizing the virtual world (as will be shown in this paper) to observe the situation macroscopically or microscopically. This may facilitate perception and control of a large number of robots in a vast and remote environment. However, most of existing VR-based interfaces rely on default hand-held equipment. They would be less intuitive than using bare hands, but also may cause potential fatigue on the user's arms for a long period of operation.

III. Methodology: Omnipotent Virtual Giant

In this paper, we propose a novel HSI framework using *omnipotent virtual giant*, which is a resizable user avatar who may perceive situations macroscopically in virtual space but also can interact with swarm robots by using bare hands, e.g. simply picking and placing them. Technically, this concept can be implemented by integrating virtual reality (VR) and Leap Motion (LM). Our proposed method has both advantages of tangible interactions giving intuitiveness as well as VR-based interactions giving remote operability.

A. Preliminary

1) Virtual Reality: VR is considered as one of the suitable user interfaces to interact with remote robots [17]. On top of its advantages described in the previous section, using VR as the main interface device can provide practical efficiency in research and development (R&D) process. In general, developing user interfaces requires enormous human trials via numerous beta tests. This process can be accelerated, if VR is in use, by using simulated swarm robots in the initial phase of R&D, where it is very important to explore various design options within a relatively short time. For example, for real swarm robotic tests, it may take elongated time to prepare such a large number of robots (e.g. charging batteries), which can be avoidable when simulated robots are instead in use. In addition, by using robot simulators (e.g. *Gazebo*, *V-Rep*, *ARGoS* [18]) along with communication protocols such as *rosbridge* and *ROS#*, it is also possible to construct *mixed reality* [17], [19], where real robots and simulated robots coexist, and then perform a hardware-in-the-loop test with the reduced R&D resources (e.g. human power, time, and cost). Obviously, the final phase of R&D should involve proper real robot tests in fields. However, thanks to VR, unnecessary efforts can be reduced over the whole development period.

2) Leap Motion: The LM is a vision-based hand motion tracking sensor. Recently, performance of the LM has been significantly improved in the latest SDK called *Orion*. Particularly, when it is used along with *Unity*, we can exploit useful modules (e.g. Leap Motion Interaction Engine) that facilitate interaction with virtual objects using bare hands without any hand-held equipment. In our previous work [20], [21], hands sensed by the LM are reasonably accurate and much more natural to use compared with the use of hand-held devices.

B. System Overview

The architecture of the proposed HSI framework, as illustrated in Fig. 1, consists of the following subsystems:

- *Mobile robots*: Swarm robots are deployed to a remote mission area. The robots are assumed to have capabilities of decentralised decision making [7]–[9], navigation and control (e.g. path planning, collision avoidance, low-level control, etc.) [22], remote inspection [23], manipulation [24], and inter-agent communication. They behave autonomously based on their local information and interaction with their neighbouring robots.
- *Data collection from the robots and visualisation*: The status of the robots and the environment where they are inspecting are transmitted to the master control station, where this information is assumed to be dynamically rendered in virtual reality. This communication may happen in a multi-hop fashion since the network topology of the robots is not probably fully-connected.
- *Interactions via an omnipotent virtual giant*: A user wearing a head-mounted display can perceive the swarm through virtual reality. The user's bare hands are tracked by the LM attached on the outer surface of the VR goggle, and then rendered as the hands of the avatar in the virtual space. The user avatar is resizeble to become a giant and can fly around to oversee the overall situation. The user can interact with the robots by touching them in the virtual space. The details of the user interfaces currently implemented will be described in Sec. III-C.
- *User input transmission to the robots*: When an interaction happens in the virtual space, corresponding user inputs are sent to the real robots, and they react accordingly.

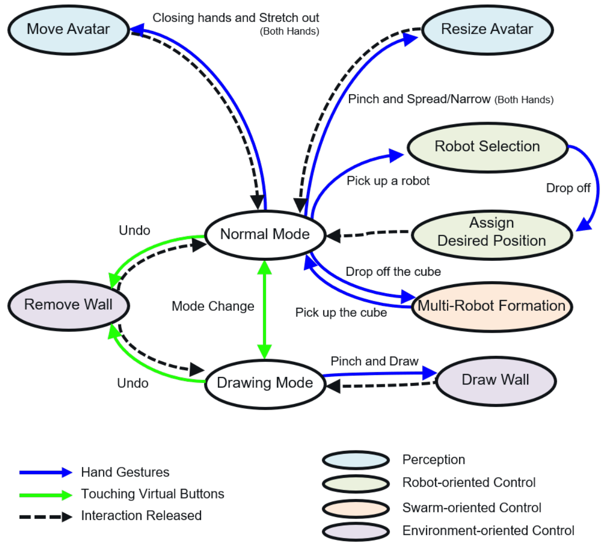

Fig. 2. A state machine representation of the proposed user interfaces

This work mainly focuses on the user interaction part of the system. It is assumed that all the other subsystems are provided, which are beyond the scope of this paper.

C. Proposed User Interfaces

This section describes user interfaces that we propose in this work. Before that, we introduce some hand gestures that are mainly used for the proposed interfaces.

- *Pinching*: This gesture is activated when the thumb and index finger tips of a hand are spatially close as shown in Fig. 3(a). *PinchDetector* in the LM SDK facilitates this gesture.
- *Closing hand*: This is triggered when all the five fingers are fully closed as in Fig. 3(b). When this is done, the variable *GrabStrength* $\in [0, 1]$ in the class *Leap::Hand* of the SDK becomes one.
- *Grasping*: This will begin if a thumb and index finger are both in contact with a virtual object. If this is initiated, the object can be grasped. One example is shown in Fig. 5. This gesture can be implemented via *Leap Motion Interaction Engine*.
- *Touching*: Using an index finger, virtual buttons can be pushed as in Fig. 6(a).

Combination of the gestures is used for perception or control for swarm robots.

1) Overall: The overall architecture of the proposed user interfaces is illustrated as in Fig. 2. There are two modes: *normal mode* and *drawing mode*. In the former, the user is able to use the interfaces for *perception*, *robot-oriented control*, and *swarm-oriented control*, whereas in the latter, the interface for *environment-oriented control* is available (the detailed description for these controls will be provided in Sec. III-C.3). Changing between the modes can be done by touching a toggle button in the menu, which can appear while the left hand's palm is facing up, as presented in Fig. 6(a).

2) Perception interfaces: For interacting with robot swarms spread in a vast arena, it is crucial to have capabilities of overall situation awareness as well as robot-level perception. To this end, this paper proposes the following two interfaces: *Resizing the world* and *Flying*.

Resizing the world: When two hands pinching are spread out or drawn together as shown in Fig. 3(a), the virtual world is scaled up or down, respectively. Meanwhile, the size of the user avatar remains unchanged. In other words, the user avatar can be a virtual giant to oversee the situation macroscopically (Fig. 3(c)) or become as small as an individual robots to scrutinize a specific area (Fig. 3(b)).

Flying: The user avatar hovers above the virtual world, not being under gravity. The avatar can fly towards any direction by closing two hands and then stretching out the arms towards the direction intended to move. Specifically, as shown in Fig. 4, with respect to the middle point of the two hands starting the closing-hand gesture (represented as the green circle in Fig. 4(a)), the relative displacement vector to the current middle point (represented as the green arrow in Fig. 4(c)) determines the user's intended flying direction.

3) Control Interfaces: User interactions to guide and control multiple robots can be summarised as the following four categories [11], [12], [15]: *robot-oriented*; *swarm-oriented*; *mission-oriented*; and *environment-oriented*. In robot-oriented interaction, a human operator overrides an individual robot's autonomy, giving an explicit direct command, e.g. teleoperation. Swarm-oriented interaction uses a set of simplified degrees of freedom to control swarm robots, for example, controlling a leader robot followed by some of the other robots. In mission-oriented interaction, a human user provides a mission statement or plan to swarm robots as a higher-level interaction. For swarm or mission-oriented interactions, collective autonomy or swarm intelligence takes a crucial role to achieve the desired emergent behaviour. Environment-oriented interaction does not affect the autonomy of any single robot, instead modifies the environments which the robots interact with, for example, by creating virtual wall or obstacles.

In this work, we present one interface per interaction mode except mission-oriented one, which are as follows: *Pick-and-Place a Robot* (for robot-oriented interaction), *Multi-robot Controlling Cube* (for swarm-oriented one), and *Virtual Wall* (for environment-oriented one).

Pick-and-Place a Robot: When the user avatar grasps a mobile robot, the robot's holographic body, which is its *target-to-go* object, is picked up and detached from the robot object, as shown in Fig. 5. Once the target-to-go object is relocated to any position, then the position is assigned to the robot as its next destination and it moves towards there while neglecting its existing assigned task. For controlling mobile robots in two-dimensional space, we set that the target-to-go object follows gravity so that it can be located on the virtual floor eventually even if the user just drops it in the air.

Although this paper only shows an example implementation for mobile robots in two-dimensional space, the pick-and-place interface can provide more benefits when con-

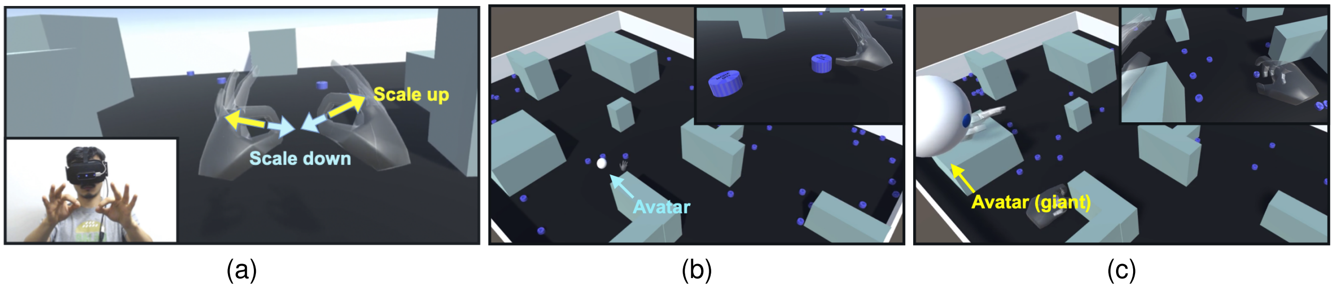

Fig. 3. Perception interface #1 - Resizing the world: Using this interface, a user can have (b) an ordinary perception, or (c) macroscopic perception for which the avatar becomes a virtual giant. In (b) and (c), the white oval object indicates the avatar's head, and the upper-right subfigures show the user's view.

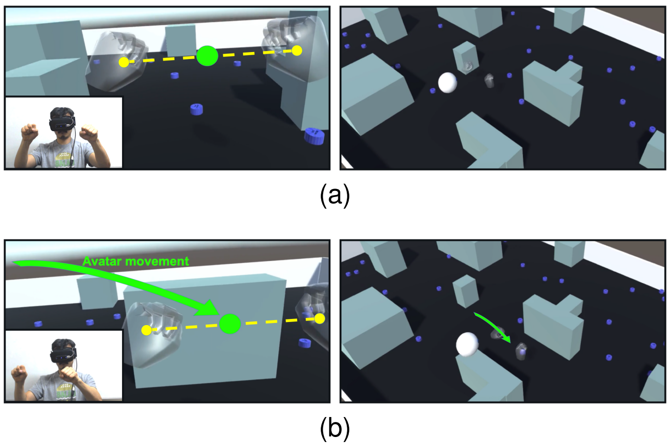

Fig. 4. Perception interfaces #2 - Flying: Using the interface, the avatar can fly to any direction above the virtual world by closing both hands and then stretching out them towards the direction intended to move ((a) before; (b) after the movement)

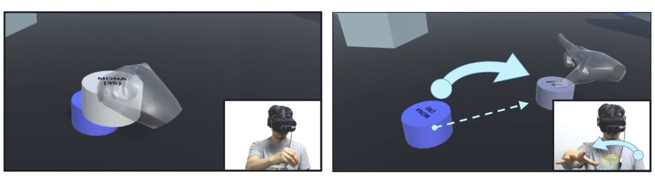

Fig. 5. Robot-oriented interface: picking and placing a robot

trolling drones in three-dimensional space, compared with a gesture simply pointing a target destination. For example, the pointing gesture generally needs an environmental surface (e.g. wall or ground) to specify a target point, but it may not be straightforward to give an airborne destination to a drone by using this gesture. The proposed interface could also easily specify not only a desired position but also a target orientation, which may be required when a robot should perform an inspection task from a certain view.

Multi-robot Control Cube: The user can have a small hand-held menu by rotating the left-hand palm to face up, as shown in Fig. 6(b). On the top, there is a pickable cube, which can serve as a virtual guided point of multi-robot coordination, e.g. the virtual centre of a rotating formation control [25]. In this work, this formation control is activated once the cube is placed on the floor.

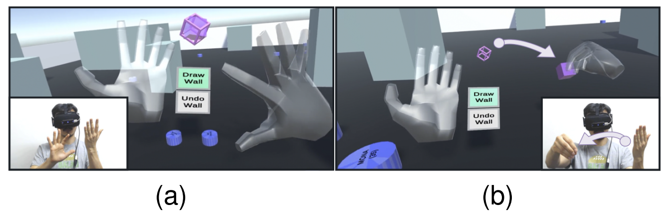

Fig. 6. (a) The hand-held menu for switching interaction modes; (b) Swarm-oriented interface: multi-robot control cube

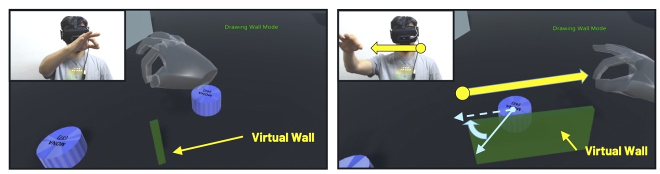

Fig. 7. Environment-oriented interface: creating a virtual wall

Virtual Wall: In the hand-held menu shown in Fig. 6(a), there are two buttons: *Draw Wall* and *Undo Wall*. By touching the former, the *drawing mode* is toggled on. In the mode, a pinching gesture creates a virtual wall, as shown in Fig. 7. Each robot is instructed to avoid these virtual walls, and thus they can be used to indirectly guide the robot's path or confine the robot within a certain area. The walls can be cleared out if the undo wall button is pushed in a last-come-first-served manner. For its simple implementation with consideration of reducing the required communication to the robots, we set that a linear wall is created, although the interface could draw any nonlinear types of obstacles. For a linear wall, its two end positions (i.e. the positions where a pinching gesture starts and finishes) projected on the virtual floor are broadcasted to the robots. Then, the robots locally regenerate additional intermediate points depending on their collision avoidance radii, and perform collision avoidance behaviours against all the points, which are the corresponding discretised linear wall.

An advantage of using virtual walls is efficiency particularly when the human operator provides general instructions to all the robots. For example, for a case where there is an area to which robots should not enter, drawing a virtual wall in front of the area easily prevents them from entering there, while allowing the robots to keep their existing autonomy. This enables the human operator to focus on another intervention that needs the operator's swift decision-making.

IV. Experimental Analysis

A. Experimental Validation using Mixed Reality

Proof-of-concept experiments to validate the proposed HSI framework use a mixed reality environment where three real MONA robots [2] (whose height and diameter is 40 and 74 mm, respectively) and six virtual robots are moving around a 90×150 cm of arena. In these experiments, the robots perform a random walk unless the human operator intervenes their movements. Each robot is capable of simple collision avoidance against virtual (or real) walls and other robots. Their localisation relies on a low-cost USB camera-based tracking system [26], which obtains the planar positions and heading angles of the real robots in the arena and sends the information to the master control computer. The master system consists of a computer executing the implemented Unity application on Windows 10, which renders the virtual world, and another computer running ROS on Ubuntu 16.04, which sends user inputs to the real robots via an antenna.

An experimental demonstration for the pick-and-place interface is presented in Fig. 8. In virtual reality, once the target-to-go object of a robot is picked up and placed as in Fig. 8(a), the robot is able to move towards the destination.

Fig. 9 shows another demonstration for the multi-robot control cube interface. In this test, only the real robots are used and the distributed rotating formation control algorithm in [25] is implemented on each of the robots. Once a human operator places down the cube object, the robots start to rotate around it. As soon as the cube is relocated as in Fig. 9(a), their formation is also changed accordingly as in Fig. 9(b).

A demonstration for the virtual wall interface is shown in Fig. 10. Regardless of whether robots are real or virtual, their behaviours are restricted by the virtual walls created by the user. All the demonstrations were recorded and can be found in our YouTube link[1].

B. Usability Study

In this section, we study i) the usability of our interfaces; and ii) how effective multiple interaction methods are for controlling swarms.

1) Mission Scenario: The swarm robotic mission that was designed for the usability study is a multi-robot task allocation. The objective of the mission is to distribute 50 virtual mobile robots over the three task areas according to their demands (i.e. 25, 15, and 10 robots, respectively), as shown in Fig. 11. The local behaviour of each robot was designed to move forwards until it faces an obstacle, then the robot performs a collision avoidance routine by rotating randomly. The simplified intelligence would require a human operator's intervention to address the given mission efficiently. For this test, all the perception and control interfaces in Sec. III-C were used except the one for formation control.

[1]https://youtu.be/2zXI6aRz3rw

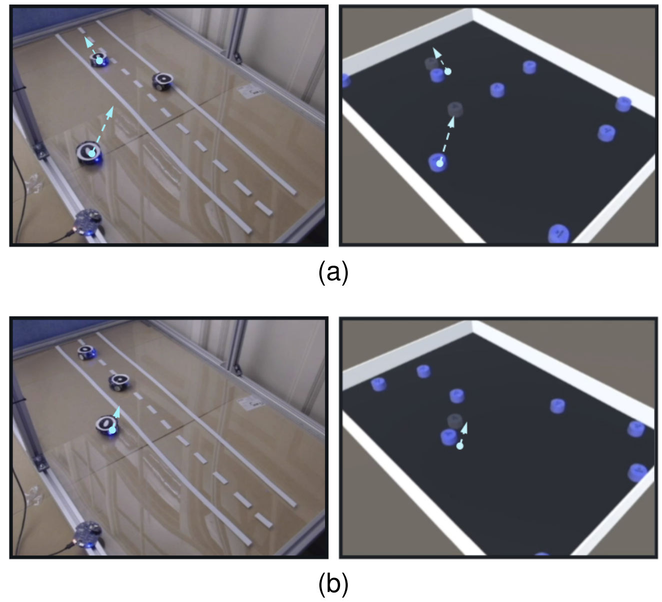

Fig. 8. Experimental validation of the pick-and-place interface: (a) once the holographic objects of robots are relocated, (b) the real robots move towards them. The left subfigures show the real robots, and the right subfigures show their visualisation in the virtual space and the other virtual robots. The dashed arrows indicate the remaining journey to the target objects.

2) Participants: We recruited 10 participants aged between 20 and 35 from an engineering background. Half of them had some experience with VR. Since all of them had never used the LM before, they were given a five-minute trial of an introductory application called *Blocks*[2] before starting the main test. Our Institutional Review Board approved this research and participants were paid for their time.

3) Experimental Setup: Each participant was provided two strategies to address the mission. In Strategy 1, the participants could only use the pick-and-place interface for controlling the robots. In Strategy 2, the participants was also allowed to use the virtual wall interface. They were instructed that virtual walls should be used to block any task arena that already possesses the required number of robots in order to prevent it from taking any extra robots unnecessarily. All the perception interfaces were allowed to be used for both strategies.

Each participant performed the mission using the two strategies respectively, for each of which, two trials were given. The trial minimising the completion time was chosen as his/her best performance, and the completion time and the number of interactions they used were recorded. The participants were also asked to fill a Likert scale survey form to quantify their experience on the individual interfaces as well as the overall system.

4) Results and Discussion: Table I shows that, overall, the proposed system allowed the untrained operators to guide 50 robots in about five minutes. Specifically, Strategy 1 (i.e. the pick-and-place interface only in use) on average requires less time (i.e. 43 sec less) but more interactions (i.e. 6.1 interactions more), compared with Strategy 2 (i.e. virtual

[2]https://gallery.leapmotion.com/blocks/

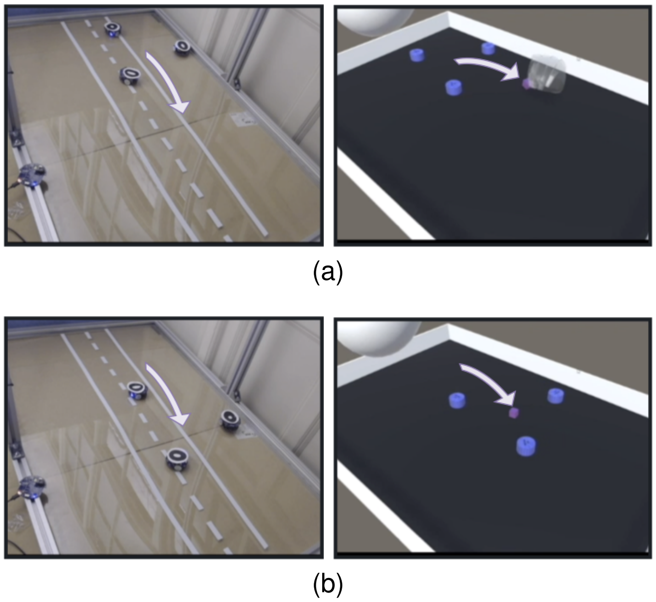

Fig. 9. Experimental validation of the multi-robot control cube interface for rotating formation control: (a) once the purple cube object is placed down, (b) the robots forms a circular formation with regard to the cube's position.

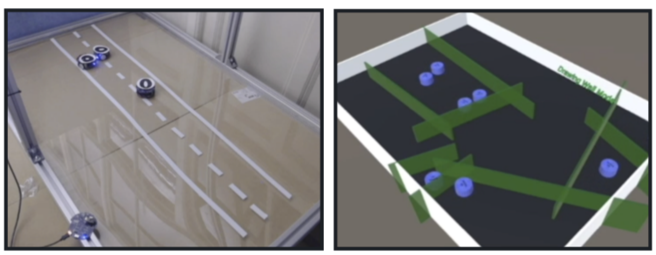

Fig. 10. Experimental validation of the virtual wall interface: due to the virtual walls (i.e. the green linear objects in the right subfigure), the real or virtual robots are confined within certain spaces.

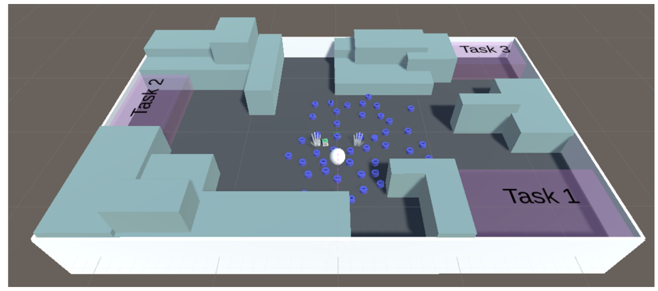

Fig. 11. The mission arena for the usability study: each participant has to allocate 50 mobile robots according to the task demands (i.e. 25, 15, and 10 for Task 1, 2, and 3, respectively). The white oval shape represents the user avatar at the time when the mission starts.

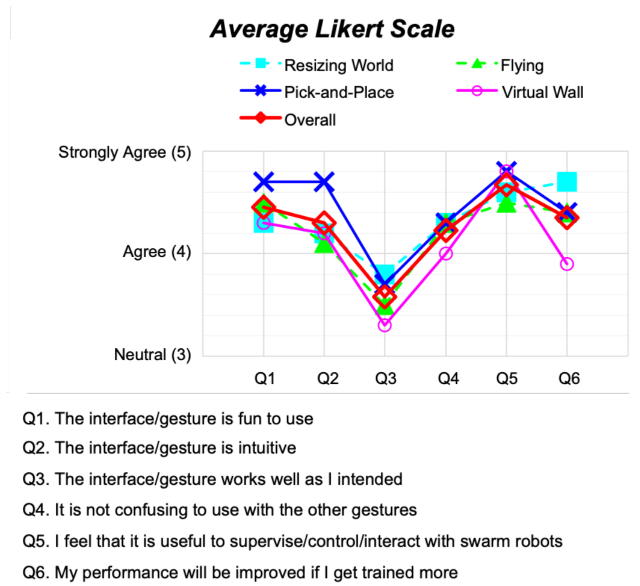

Fig. 12. Qualitative Comparative Result of HSI

walls also in use). This indicates that using environment-oriented controls could reduce the needs of explicit one-by-one guidance towards individual robots, ending up with reduction in the total number of interactions. However, the increased completion time in Strategy 2 implies that a user may be confused with multiple modalities, especially, when the interfaces are similar to each other. The same tendency was also found for experienced users (i.e. the developers of the proposed system).

Fig. 12 presents the user experience result of the proposed system. The average answers for Q3 imply that users may need more training to use the LM. In fact, during the test, it was often observed that the participants unconsciously stretched out their hands out of the LM's sensing range. The result could be considered obvious due to the fact that the end-user interface with VR and the LM was definitely unfamiliar to the participants. The answers for Q6 indicate that the resizing world interface relatively needs more training, whereas the virtual wall interface is easier to use. In contrast, the virtual wall interface was selected as the most confusing one, as in the results for Q4. This seems to be relevant to the increased completion time in Strategy 2 as in Table I, because the pinching gesture is used to create virtual walls as well as to resize the world, but in different toggle modes, respectively.

However, it was mostly agreed that the proposed HSI framework would be useful for interaction with swarm robots, as in the result for Q5. Obviously, the pick-and-place interface is the most fun and intuitive according to the results for Q1 and Q2.

TABLE I

AVERAGE PERFORMANCE

	Strategy 1 (PP)		Strategy 2(PP+VW)	
	Ave	Std	Ave	Std
Completion time (sec)	269.9	60.8	312.8	70.6
The number of interactions	27.5	6.8	21.4	6.9

PP: Pick-and-Place interface; VW: Virtual Wall interface

V. CONCLUSIONS

In this paper, we proposed an intuitive human-swarm interaction framework using a super-powered user avatar who can supervise and interact with a swarm of robots in virtual reality, which is implemented by VR and Leap Motion. This work introduced two perception interfaces, by which the user avatar can resize the virtual world or fly around the scene, and three control interfaces for robot-oriented, swarm-oriented, and environment-oriented interactions, respectively. We presented the results of proof-of-concept experiments to validate the proposed HSI framework by using three real mobile robots and six virtual ones in a mixed reality environment. A usability study for a multi-robot task allocation mission was done to evaluate the proposed framework. The results suggested that the proposed system could be suitable for swarm robots in a vast and remote environment, and that the individual interfaces using bare hands are intuitive and fun. It was also shown that multiple modalities could reduce the number of human interventions (i.e. workload), but may increase mission completion time, especially if the user is not trained enough, due to its inherent complexity.

For real world applications, the communication capability of swarm robots to a human operator will be one of the big challenges. Considering any possible network topology, the larger number will impose huge communication load on the near-end robots as well as bottleneck information flow. Eventually, this will lead to a latency of remote visualisation for the operator. Therefore, the near-end robots or any robots in the middle may need to make decisions in terms of which information from which robots needs to be prioritised in order to maximise the operator's perception, while reducing communication load imposed on the near-end robots.

The proposed system can be regarded closer to a multi-robot system than a true swarm because all individual robots are connected to a centralised control centre in this work. For a truly decentralised swarm, the system also should include appropriate swarm intelligence, which are embedded in each robot and robust against more complex networks, so that a desired collective behaviour can still emerge even if the human node is only connected to a part of the robots.

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